Wat. Sci. Tech. Vol. 22, No. 3/4, pp. 217-224, 1990.
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0273-1223/90 $0.00 + .50
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ZERO DISCHARGE THROUGH INNOVATIVE APPLICATION OF INTENSIVE SILVICULTURE TO EFFLUENT DISPOSAL FROM A SMALL CANADIAN WASTEWATER TREATMENT PLANT

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ABSTRACT

The design and practical experience gained from the operation of a small activated sludge wastewater treatment facility, incorporating zero effluent discharge through evapotranspiration utilizing a multi-clonal poplar forest, is described. Secondary treated effluent was seasonally applied to a forested plantation through an automated sprinkler system with the rate being calculated daily based on information from an automatic weather station and using a modified Penman approach. For the past six years, significant growth rhythm differences were found amongst the poplar clones. The influence of effluent irrigation on growth, with its additional nutrient content, is positive but not as yet deemed significant. Work to date would suggest that evapotranspiration of effluent by the plantation can be 3-4 times greater as compared to grass. This is attributed to increased foliage, larger direct evaporation and advection. Since the structure of plantation can be manipulated to a certain extent, it is speculated that further increases of evapotranspiration can be obtained even in a sub-humid climate. The concept could be applied in various geographic areas with existing technology and software allowing for the complete automation of an effluent recycling system.

KEYWORDS

Small sewage treatment plant; effluent spray irrigation; zero discharge; evapotranspiration; recycling; intensive silviculture; poplar; forest.

INTRODUCTION

The disposal wastewater from small rural communities (remote from communal sewerage systems) such as resorts, boarding schools and community colleges can be accomplished by means of land application utilizing leaching beds of various designs. Essential considerations for the design of such systems are: total amount of treated wastewater, rate of flow, depth of groundwater, soil texture and vegetation cover. However, in certain situations this method may not be suitable and alternate solutions must be found, especially where there is a mandated requirement for a zero effluent discharge and a desire to reduce the potential for infiltration of effluent residuals into the groundwater. The application of intensive silviculture for the disposal of treated effluent offers such an alternative.

The disposal of treated wastewater through evapotranspiration represents an important component of the systems presently based on effluent sprayed over grass. However, such systems require considerable land areas and appropriate soil texture in order to minimize the risk of residuals leaching to the groundwater. While the evapotranspiration of grass cover is limited and cannot be manipulated, a forest canopy is confronted with a much increased atmospheric demand for evapotranspiration (Pruitt and Snyder, 1985). Also, because the

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structure of the canopy can be manipulated to a certain extent and its foliage and soil can be resupplied at short intervals, the actual evapotranspiration of the forest can be somewhat stimulated, even in a sub-humid climate (Larson, 1981). With its deep roots and the much larger and exposed foliage, a forest plantation presents additional advantages for effluent recycling; it can retrieve water from deeper layers, recycle the nutrients more actively and it can be harvested periodically resulting in yields that are not used in the food chain. In a plantation especially created for effluent recycling, it is sought to achieve, by cultural and genetic means, the maximization of both the atmospheric demand for evapotranspiration and nutrient uptake. Poplars and willows with their fast growth, known tolerance to humid environments and high nutrient requirements, especially for nitrogen, appear well suited for such systems.

The literature dealing with the evapotranspiration related aspects of the grassed effluent disposal areas is at best scarce. Summarizing a number of experimental lysimeter studies, an EPA report recommends the standard 'pan' evaporation as design criterion for the grassed areas (Bennett and Lindstedt, 1978). Considerably more information about the atmospheric demand for evapotranspiration exerted on a grass cover can be found in the agricultural literature (Doorenbos and Pruitt, 1977; Burman et al., 1983), where the Penman combination approach was calibrated for grass and serves as a standard for the irrigation rate calculation for short and dense crops.

A number of existing wastewater disposal projects in forested areas established in the last three decades have been located on permeable soils, thus having a very short effluent residence time in the root zone and, consequently, little benefit from evapotranspiration (Sopper and Reichenderfer, 1978; Barton, 1984). Since the application rates in one these projects was not tied to the consumptive use of the forest, but was fixed instead to an amount equal to precipitation, nitrates appeared in the groundwater in less than three years (Simpson and Cunningham, 1978). Adoption of forest evapotranspiration to effluent treatment technology and determination of the 'carrying capacity' of forested stands with different structures to perform this treatment, while at the same time preventing the groundwater contamination, may represent the key for an ecologically sound land application at rates based on recycling rather than disposal.

This paper describes an installation at Seneca College of Applied Arts and Technology in King City, Ontario, Canada (Lat. 43°, 58' N, Long. 79°, 31' W). Seneca College, King Campus is a community college within a rural setting. The campus covers approximately 280 hectares of rolling farmland and bush and includes a 20 hectare lake. The present wastewater system design can serve a student population of 1800 plus 300 staff and 100 individuals from an on campus Management Development Centre for a student equivalent design population of 2200. This equates to a total population equivalent of 600 based on an average day per capita flow rate of 0.454 m^3d^{-1} (100 Imp. gallons per day). The design of the facility took into account the varying flows over the winter and summer periods and for the loadings that are experienced during the weekdays versus the weekends within each period. Also, due allowance was made for additional recreational uses of the Campus during the winter and summer weekends (i.e. cross-country skiing in winter and picnics in the summer). The wastewater treatment and effluent disposal system consists of two small activated sludge plants, a treated effluent holding pond and an automated in-ground, seasonal spray irrigation system based on the evapotranspiration of a forest plantation. The forested plantation portion of the system has been in operation since 1983. All sewage is pumped to the plant via a submersible pumping station utilizing 3 small duty pumps operating in demand sequence thus reducing the hydraulic variations to the plant.

The climate of King City, Ontario is characterized by a normal mean annual temperature of 6.4°C and a normal sum of precipitation of 770 mm, of which 410 mm is rainfall during 1 April to 30 September. The warmest month of the year is July, with an average monthly temperature of 18.5°C and an extreme maximum of 38.5°C. However, the high air relative humidity during summer substantially reduces the atmospheric demand for evapotranspiration.

DESCRIPTION OF FACILITIES

The original treatment/effluent disposal facility with an initial capacity of 136 m^3d^{-1} was commissioned in the mid 1970's with several additions/extensions over the years resulting in a present day facility as described as follows.

Treatment Plant

Raw sewage is treated in two small activated sludge plants with a total design capacity of 272 m^3d^{-1}. The plants incorporate: comminution, coarse bubble diffused aeration, final settling and hypochlorite disinfection prior to discharging to an effluent holding (storage) pond. All sludge is digested aerobically prior to offsite disposal.

Effluent Holding Pond

The treated effluent is discharged into a single large pond (Fig. 1a). The capacity of the effluent holding pond is 66 780 m^3 at a liquid depth of 3.35 m. The volume of the pond was established by considering the weekday, weekend and infiltration flows plus net precipitation. The liquid surface area is approximately 2.4 hectares. In order to assure aerobic conditions in the pond at all times, a "tube type" aeration system positioned along the floor bottom provides a small amount of air. The pond was designed to store the effluent over a 265 day fall/winter/spring period.

Automated Spray Irrigation System

The contents of the effluent holding pond plus the treated summer flows are sprayed on the adjacent land over an average 100 day summer period. The irrigation system is an in-ground facility with the effluent sprayed through a series of rotating sprinklers located atop 1.5 m steel risers and staggered for optimal coverage. Each sprinkler is controlled through an electrically controlled solenoid valve. The sprinklers are of the 'Rain Gun' type with nozzle diameter of 28 mm and operate at about 7 atm (Fig. 1b). The "throw" radius is approximately 45 m in an open field. In plantation, the radius is reduced to about 25 m, due to crown obstruction of the jet. For pressure stability, the sprinklers are normally divided in 8 clusters of 3 sprinklers each. Each cluster is controlled by an automatic timer located at the pumping station. However, the sprinkler control system can be programmed to operate any 3 sprinklers within the spray area at any given time. The total spray area is approximately 15 hectares.

The original design spray application rate for initial grassed area (Fig. 1b., years 1975 to 1982) was 56.2 m^3d^{-1} per hectare (5000 Imp. gallons per acre per day).

Fig. 1a. Effluent holding pond

Fig. 1b. Sprinkler (original grass)

Site and Soil

The local topography of the spray irrigation area is moderately rolling, with numerous depressions in which the meltwater created small, sometimes laminated, deposits of silt and clay. The local soil is a till moraine, of silt to clay texture with a few boulders. Certain areas are characterized by a poor drainage, especially in depressions. The natural forests in the surrounding area are composed of red oak and maple mixtures of medium to high productivity. This particular area is of average agricultural fertility. Due to the short growing season, it was previously farmed mostly for hay production.

METHOD

Weather Monitoring

Weather information was obtained with an automatic weather station based on a computerized micrologger programmed to provide 10 minute averages or sums for the following parameters:

global solar radiation, air temperature, air relative humidity, wind speed and rainfall. Data was initially stored in the micrologger's internal storage and then transported via magnetic tape to an IBM-AT computer where it was archived.

Irrigation Computer Software

The daily weather files were used primarily for the calculation of the potential evaporation, ETp, using the Penman model in the 'grass standard' version given by Doorenbos and Pruitt (1977). The advantage of using this version of the model resides in the fact that it was field calibrated with a worldwide data set, as opposed to other American versions of the grass standard that were validated only for the Western USA (Burman et al., 1983). Then ETp 'grass' was corrected for the potential evapotranspiration of the poplar stand ETp 'forest', using the coefficients devised by Item (1974). These correction coefficients, modifying both the 'heat' and the 'aerodynamic' term in the Penman model, take care of the albedo and the roughness length which are considerably different in the case of a stand of trees in comparison with the 'grass standard'. Other correction coefficients account for the direct evaporation from the foliage when wet and the control exerted by the soil water availability on the transpiration rate. These modifications of the model result in a considerably increased ETp 'forest' versus the initial ETp 'grass'.

Tree Plantation

The previously grassed sprayfield (years 1975 to 1982 Fig. 1b.) was planted in stages between 1983 and 1986 with various clones of hybrid poplar, Populus and willow Salix (Fig. 2a. and 2b.). A small grassed area, about 0.5 hectare, was not planted, to serve as a reference for further studies. Each year, previous to the spring planting season (May in Ontario), the soil was ploughed to 25-27 cm and then treated with herbicides in order to reduce the competition from grass and annual weeds. The 1983 plantation was established with one year-old rooted cuttings, while for the rest of the plantings unrooted cuttings were used. The results herein relate to the 1983 (oldest) plantation. This plantation was made with the following clones:

- **AK-30** (P. alaba, Ontario x P. glandulosa, S. Korea),
- **C-147** (P. canescens 9B, Germany),
- **DN-173** (P. x euramericana 'Dorskamp', Holland),
- **GA-88** (P. grandidentata x P. alaba, Ontario) and
- **NM-5** (P. nigra x P. maczimowiczii, 'Max-4', W. Germany).

These clones were planted in 5 replications of 7 rows by 10 trees spaced at 4 x 4 m. The total area of the 1983 plantation was 2.65 ha. The soil of the plantation was maintained in the first three years by disking. In order to secure an easy air circulation in the plantation, the trees were pruned up to 2.5 m in early 1987.

Fig. 2a. Plantation

Fig. 2b. Sprinkler in plantation

Growth Measurements

In order to assess the clonal performance and the possible influences of irrigation with effluent, the diameters and heights of all the trees were measured (in November 1988). In every replication, the trees were tallyed in two categories, namely: irrigated and non-irrigated. This was necessary because the sprayed area around each sprinkler was much

restricted in the stand as compared with the open field. The measurements were statistically processed, including analysis of variance, using SYSTAT (Wilkinson, 1988).

Effluent Analysis

Analyses were performed in order to provide an insight into the efficiency of the treatment process and an indication of the nutrient load. The results of recent sampling on the raw sewage and plant effluent are as noted in Table 1.

TABLE 1 Raw Sewage and Effluent Analysis*

(all units mg^{-1})

ITEM	RAW SEWAGE	PLANT EFFLUENT	ITEM	RAW SEWAGE	PLANT EFFLUENT
BOD_5	258	8	Na	44	43
BOD_s	96	4	Cl	44.1	31.1
SS	218	10	K	21.0	14.5
TKN	82	22.8	Mg	19	20
NH_3	40.1	16.1	Mn	0.08	0.09
NO_3	0.42	4.97	Fe	2	< 1
NO_2	0.012	0.017	Cd	< 0.02	< 0.02
P_T	9.6	6.6	Mo	0.04	0.08
P_s	4.9	4.6	Cr	0.04	0.03
Ca	91	87	Co	< 0.01	< 0.01
Zn	0.13	0.14	Ni	0.02	0.02
Cu	0.30	0.05	Ag	< 0.01	< 0.01
Pb	< 0.05	< 0.05	Ti	< 0.1	< 0.1

* Sample partially frozen

Clonal Performance

As expected (because the clones used in the 1983 experiment are not closely related), there were important differences found between clones with respect to dimensions attained after 6 years in both the irrigated and non-irrigated regimes. The analysis of variance for diameter and height of clones after 6 years are given in Table 2.

TABLE 2 Statistical Analysis for Poplar Clones' Growth

CLONE	NON-IRRIGATED					IRRIGATED				
	trees	diameter		height		trees	diameter		height	
	no	cm	homog.	m	homog.	no	cm	homog.	m	homog.
AK-30	171	9.94	B	9.43	C	150	10.27	B	9.02	B
C-147	225	7.02	A	6.99	A	96	8.29	A	8.00	A
DN-173	240	13.14	D	11.03	D	100	12.55	C	11.25	C
GA-88	168	10.00	B	8.30	B	133	9.09	A	8.07	A
NM-5	257	11.80	C	9.40	C	87	11.20	B	8.88	B

Two-Way ANOVA for clone x irrigation effects: Exp. F val./Transg. Probab. (%)
- diameter: clone 165.46/.00; irrigation .47/.49; combined 7.45/.00
- height: clone 226.77/.00; irrigation .03/.85; combined 11.87/.00

The most significant influences were exerted by the clonal effects, both for diameter and height growth; large experimental F values for clones. The largest growth, both for diameter and height, was experienced by the clone DN-173 while the clone GA-88 is positioned at the other side of the dimensional range. Up to this age, the irrigation did not result in significant differences; experimental F values less than 1 and the transgression probabilities over 49% for diameter and 85% for height. This result can probably be

explained through the fact that, under this climate, normally with rains at intervals no longer than a week, the non-irrigated trees did not experience severe water stresses conducive to growth differences.

Climatic Variability of Rains and Evapotranspiration

The climate of King City, Ontario, Canada can be considered sub-humid. A detailed multi-annual rainfall analysis performed on historic weather records in Southern Ontario shows a high frequency of natural precipitations, particularly during the growing season (Fig. 3). When the interval between 1 April and 30 September of various years (not shown here) is divided in clusters of 'dry' and 'wet' days, one can note that between 45 and 75 such changes occur during one growing season, with the 'dry' intervals lasting 2 to 7 days and the 'wet' ones between 1 and 3 days. Daily ETp 'grass' calculated on the basis of these historic records strongly reflect these changes, which in fact represent constraints for such an effluent irrigation activity in which the objective of recycling of the liquid fraction is accomplished predominantly through evapotranspiration.

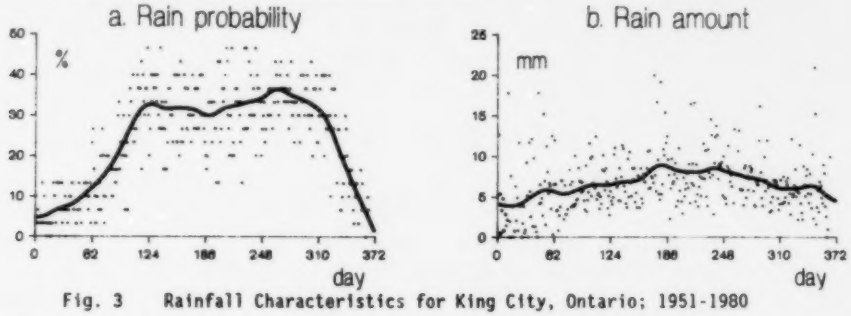

Fig. 3 Rainfall Characteristics for King City, Ontario; 1951-1980

An analysis of the daily ETp 'grass' for the period 1972-1981 (not presented here) has shown that locally this index can reach values as high as 7.5 mmd^{-1}. These calculations were confirmed by the actual evapotranspiration of a grass cover measured with a large lysimeter installation in nearby Woodbridge, Ontario. In Fig. 4, a comparison between the potential and actual ET is given for the year 1979. It is evident that the clusters of 'wet' days depress considerably both the potential and actual ET. Also, after an abundant rain or a rainy interval the actual ET is equal to potential ET, while close to the end of a cluster of dry days the potential ET cannot be satisfied by a depleted soil water reservoir. As a consequence, the maximization of recycling under such a climate implies sizing the daily spray rate according to the daily atmospheric demand for evapotranspiration.

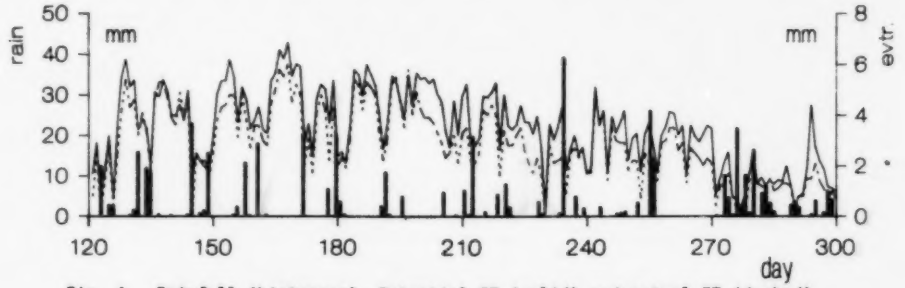

Fig. 4 Rainfall (histogram), Potential ET (solid) and actual ET (dashed) for Grass Cover in 1979; Woodbridge, Ontario

The Irrigation Regime Applied to Plantation

During the growing season of 1987, when the plantation was in the fifth year, irrigation was practised between 26 May and 29 August. Below a crude water balance of various fields during this interval is presented for both grassed areas and poplar forest (Table 3).

TABLE 3 Mass Liquid Balance for Grass and Poplar Forest

	RAINFALL mm	IRRIGATION mm	ETp mm	EXCESS IRRIGATION mm	UNUSED CAPACITY mm
Cut grass	315.8	754.6	283.6	865.4	78.6
Wild grass	315.8	754.6	354.6	815.6	99.8
Poplar forest	315.8	754.6	1135.6	396.3	461.5

The potential evapotranspiration rates of the three ecosystems during a whole growing season appear to be quite different. As compared to the grass standard, the wild (uncut) grass had an increase of about 30% while the increase for the poplar canopy was about 407%. It should be noted that irrigation with a rate that is more than double that of the rainfall for the same interval caused considerable runoff from the grassed area, while no ponding or runoff was recorded in the stand of trees. Since the local soil has a very low permeability, and in less than two hours after applications amounting to 5-7 mm, the soil in the plantation was again trafficable, is indicative of the magnitude of consumptive use of poplars versus grass. It is believed that a good proportion of the application rate was intercepted by the foliage and evaporated directly. However, it is not possible at this time to state what this proportion was nor how it would be increased by splitting the daily irrigation rate into more numerous applications. This liquid recycling rate surpasses by about 25% the forest evapotranspiration determined by Morton (1988), probably because of additional advection effects in a well spaced poplar plantation.

A special irrigation strategy should be applied for sites with high soil permeability. In order to prevent percolation, which will certainly result if the whole daily rate is delivered in one application, the daily rate should be split into a number of waterings, to be applied only during daytime, when the solar radiation and higher than average temperature result in an increased demand for evapotranspiration. Such a strategy would increase the proportion of effluent evaporated directly from the leaves.

A daily examination of the liquid water balance for the poplar stand (not given here) revealed that some days the reprocessing capacity of the plantation was surpassed. This situation occurred mainly in days when the automatic application coincided with unpredictable rains. However, there were considerably more days in which the liquid recycling ability of the plantation was not fully used.

CONCLUSIONS

On the basis of the results of studies to date, it would appear that intensive silviculture incorporating cultivated plantations of poplars and other species can be used as biological reprocessors for treated effluent at a considerably higher effectiveness than grass. During the six years in which irrigation was practiced with secondary treated effluent, no adverse effect on the clones used was recorded. The crown development of trees increased the trees consumptive ability as well as their ability to hold and evaporate water directly from the leaves. From the results of the studies to date, it is reasoned that irrigation rates equivalent to three to four times the calculated 'grass' standard in well developed and healthy poplar stands could be considered on soils with reduced permeability in climates similar to those of King City, Ontario, Canada.

Observations made during the operation of this project have shown that the poplar clones have different behaviour with respect to foliation. Firstly, the foliation dates differ considerably, with the clone NM-5 having the longest interval 'in leaf'. Secondly, the foliage mass appears to be also different, the clone DN-173 having the largest foliar area and thus being probably the most effective consumer of both water and nutrients. Thirdly, some foliar diseases, such as Melampsora sp. and Marssonina sp., frequently found on DN-type poplars present the risk of curtailing the duration of active consumption. As a consequence, selection of poplar clones for effluent recycling is a multi-faceted process.

Improvements of system performance in the future should be based on: (a) additional research into the complex problem of forest evapotranspiration, in order to replicate the results and increase the accuracy with which the application rate is calculated on the basis of the

meteorological measurements, and (b) a means to integrate the calculated application rates with the rainfall probabilities for a specific locality.

Future performance evaluation of this concept should provide information about two additional aspects. The leaching fraction of effluent has to be determined on the basis of local measurements of hydraulic conductivity and studies with a soil-water transport model. Studies of the foliar content for some principal nutrients, especially nitrogen, should also define a nutrient 'carrying capacity' for the system during the growing season.

It is estimated that when solid knowledge is obtained about the actual forest evapotranspiration rate, local rainfall probabilities, leaching fraction, and nutrient needs of some prospective poplar clones is obtained, a facility could be operated through an expert system for reduced costs and increased effectiveness.

ACKNOWLEDGMENT

The cooperation T. Bancroft-Wilson and staff of Seneca College in King City and Ontario Ministry of Natural Resources in Maple is gratefully appreciated. Also, thanks are expressed to R. Street of Canadian Climate Centre, Environment Canada for supplying the lysimeter data.

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